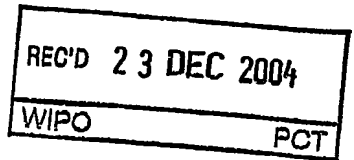**Europäisches Patentamt**

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Nozzle unit and method for excavating a hole in an object

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NOZZLE UNIT AND METHOD FOR EXCAVATING A HOLE IN AN OBJECT

The invention relates to a nozzle unit for generating an abrasive jet, which nozzle unit comprises:
- a first nozzle connected to a pressurized carrier fluid supply;
5 - a mixing chamber in which the first nozzle discharges;
- a second nozzle connected to the mixing chamber; and
- an abrasive particle inlet to the mixing chamber.

Such a nozzle unit is generally known in the field of
10 abrasive water jet machining. These machining devices operate at an ambient pressure substantially equal to atmospheric pressure. The water jet, which is virtually free of any solids, is jetted into the mixing chamber at a pressure of well above 1kbar. The dry abrasive material
15 is kept at atmospheric pressure and due to the jet pump mechanism in the mixing chamber, abrasive particles are sucked into the mixing chamber through the abrasive particle inlet.

In the field of drilling holes into geological earth
20 formations, an abrasive water jet system including a nozzle unit with a jet pump mechanism can be used for drilling a hole, see for example WO 02/34653. However, the conditions in this field are substantially different from the field of atmospheric abrasive jet machining
25 since the ambient pressure is well above atmospheric pressure and increases with about 1 bar per 10 meters depth.

In the case of the atmospheric abrasive water jet machining systems, air is sucked into the mixing chamber together with the abrasive particles. This air flow into the nozzle unit may generate cavitation that can limit the transfer of kinetic energy from the water jet to the abrasive material. Consequently, the efficiency of the nozzle unit, which is based on this kinetic energy transfer, is limited by the cavitation.

Another important source of cavitation may stem from turbulence in and around the jet stream. Pressure fluctuations in the turbulence locally include pressures below the vapour pressure of the carrier fluid, which possibly causes vaporization, the creation of gas bubbles, and cavitation.

International application WO-A 91/12930 mentions an efficiency reduction of conventional nozzle units when applied in increased ambient pressure conditions, and reports the construction of a nozzle unit that allows for a relatively easy modification of the mixing chamber length. This measure corrects the nozzle design for the increase in jet divergence caused by the gradual decrease of a cavitation shield around the jet with ambient pressure.

It is an object of the invention to provide a nozzle unit that can be used for excavating a hole into an object, such as a geological earth formation, having a substantially higher efficiency than when a nozzle unit according to the state of the art is to be used.

In accordance with the invention there is provided a nozzle unit for generating an abrasive jet, which nozzle unit comprises a first nozzle connected to a pressurized carrier fluid supply, a mixing chamber in which the first nozzle discharges a second nozzle connected to the mixing

chamber, and an abrasive particle inlet discharging in the mixing chamber, wherein the proportion of the cross sectional area of the first nozzle opening and the cross sectional area of the second nozzle opening is in a range of 0.50-1.0.

It has been found that the larger the cross sectional area of the second nozzle is sized compared to the cross sectional area of the first nozzle the more abrasive particles need to be entrained in the flow of the carrier fluid in order to achieve a substantial amount of kinetic energy transferred from the jet stream created by the first nozzle to the entrained abrasives. This transfer of kinetic energy can be considered to be the efficiency of the nozzle unit. If the proportion between the nozzle cross sections is less than 0.5, a too large amount of abrasive particles is required to fill the space in the second nozzle causing problems to supply the abrasive particles. On the other hand, the cross sectional area of the second nozzle should always be larger than the area of the first nozzle, i.e. a proportion of less than 1, in order to accommodate at least some entrained abrasives in addition to the high pressure jet stream.

Unlike the design of the nozzle unit described in WO-A 91/12930, the nozzle unit according to the invention is optimized to accommodate the supply and relative flow rates of gas, the carrier fluid and the abrasive particles.

It is believed that for this reason the nozzle unit according to the invention has been satisfactory operable under high ambient pressure, in particular at an ambient pressure of higher than 50 bars, or of even higher than 300 bars. The nozzle unit is therefore particularly

suitable for application in subterranean earth formations at depths exceeding several kilometres up to 10 km.

Preferably the upper limit of said range of cross sectional areas is 0.9, so as to ensure that a sufficient number of abrasive particles can be entrained in the flow of carrier fluid.

In a preferred embodiment of the invention the length in the flow direction of the mixing chamber is such, that taking into account the divergence of the jet from the first nozzle, the diameter of the jet leaving the mixing chamber is smaller than the diameter of the second nozzle opening. A submerged jet typically has a divergence of 8°-9°. The length is defined as the distance between the exit opening of the first nozzle and the entry opening of the second nozzle. The entry opening is the first point, where the smallest cross-section is present.

In an embodiment of the invention the length of the mixing chamber is in the range of 0.8-2.0 times the diameter of the first nozzle opening. This provides for an efficient mixing of the abrasive particles with the jet, while keeping the length of the mixing chamber limited. This has the advantage, that the jet can be placed under an angle, which is necessary when drilling holes. When using the nozzle unit according the invention, the nozzle is rotated, such that a hole with a substantial circular cross section is generated.

In view of this use, it is furthermore preferred that the length of the second nozzle is in a range of 4-10 times the second nozzle diameter.

In an embodiment of the invention, the second nozzle is eccentrically arranged relative to the first nozzle with respect to the flow direction. Preferably the eccentric displacement of the second nozzle has a

component in the direction of the abrasive particle inlet. Herewith it is constructionally easier to keep the smallest dimensions of the abrasives supply opening substantially equal to the diameter of the first nozzle, while maximizing the proportion of the cross sectional area of the first nozzle to the second nozzle.

The eccentric displacement is preferably up to the situation that part of the first nozzle wall is in line with part of the second nozzle wall. In the case of both a cylindrical first nozzle and a cylindrical second nozzle the eccentricity E is then equal to half the difference between the two nozzle diameters.

It is furthermore preferred that at least part of an inside wall of the first nozzle is aligned with at least part of an inside wall of the second nozzle.

In an embodiment of the invention, the nozzle unit comprises a supply channel connected to the abrasive supply inlet, wherein the supply channel surrounds the mixing chamber by an angle of less than 180°. In this way efficient use can be made of the eccentric secondary nozzle configuration when provided. At the same time, the supply inlet should be sufficiently wide to be able to supply abrasive particles without substantial risk of blockage.

The included angle between the flow direction in the supply channel and an axis along the flow direction in the primary nozzle is preferably as small as possible. This way the supplied abrasive particles get an as large as possible velocity component parallel to the jet stream generated by the primary nozzle. In an embodiment of the invention, the angle is smaller than 60°, preferably smaller than 30°. Due to mechanical constraints, the angle is typically larger than 10°.

The invention further relates to a combination of a nozzle unit according to the invention and a separation device for separating magnetical or magnetizable abrasive particles from a fluid, which separation device comprises a magnet body for attracting the abrasive particles out of a fluid flowing along the separation device, and a support surface at least partially enveloping the magnet body, and means for transporting attracted abrasive particles along the support surface to the abrasive particle inlet of the nozzle unit.

The invention also relates to a method of excavating a hole into an object, comprising the steps of:

- arranging an abrasive jet excavating tool comprising a nozzle unit according to the invention into the hole;

- generating an abrasive jet by supplying a pressurized carrier fluid to the first nozzle and discharging abrasive particles into the mixing chamber; and

- directing the abrasive jet into the object.

For the purpose of this specification, an object is understood to include primarily earth formations, including subterranean earth formations, and also cement, casing steel, or packer material in a well for the exploration or production of hydrocarbons. Such types of objects can in normal operation be located several kilometres depth under the earth surface, such that the ambient pressure can exceed 300 bars.

These and other features of the invention will be elucidated below by way of example and with reference to the accompanying drawing, wherein

Figure 1 shows a perspective view of an embodiment of the nozzle unit according to the invention;

Figure 2 shows a cross sectional view of the nozzle unit according to Figure 1; and

Figure 3 shows a schematic cross sectional view of an excavating tool comprising the nozzle unit according to the invention; and

Figure 4 (parts a to c) shows a magnetic body for use in the excavating tool of Figure 3.

In Figure 1 a perspective view of a nozzle unit 1 according to the invention is shown. The nozzle unit 1 is advantageously manufactured out of tungsten carbide based materials, for instance similar materials as used for mixing tubes in the field of abrasive water jet machining.

Also referring to Figures 1 and 2, the nozzle unit 1 has an inlet 2, for supply of a pressurized carrier fluid to the nozzle unit 1. The inlet leads to a first nozzle 3 having a first cross sectional area of A_1. The nozzle 3 may have a non-circular cross section, such as an oval cross section, but in the preferred embodiment of Figure 2 the nozzle is circular having a diameter D_1.

The first nozzle 3 discharges into a mixing chamber 5, which mixing chamber has a length along its flow direction of L_1. The nozzle unit 1 also has an abrasive particle inlet 4 that discharges into the mixing chamber 5. A second nozzle 6 is connected to the mixing chamber 5, which second nozzle 6 has a cross sectional flow area A_2 and length L_2. Like the first nozzle, the second nozzle 6 may have a non-circular cross section, such as an oval cross section, but in the preferred embodiment of Figure 2 the nozzle 6 is circular having a diameter D_2.

The second nozzle 6 is eccentrically placed relative to the first nozzle 3. The amount of eccentricity is indicated in the drawing by E. The eccentricity E in this case equals half of the difference between the two nozzle

diameters (D_2-D_1) so that the first and second nozzle inside walls on the side opposite of the abrasive particle inlet 4 are aligned with each other.

Generally, the ratio A_2/A_1 of the cross sectional area of the first nozzle opening and the cross sectional area of the second nozzle opening should be in a range of 0.50 to 1.0. The length of the mixing chamber best lies in a range of 0.80 to 2.0 times D_1. The length L_2 of the second nozzle best lies in a range of 4 to 10 times D_2.

In the preferred embodiment as shown in Figure 2, the ratio A_2/A_1 is 0.56 (corresponding to $D_2/D_1 = 0.75$). The length L_1 of the mixing chamber is 1.1 times D_1; the length L_2 of the second nozzle 6 is 7 times D_2.

Visible in Figure 1 is a supply channel that is connected to the abrasive supply inlet 4, and that surrounds the mixing chamber by an angle α. The angle α is preferably more than 90° and less than 180°, and in the preferred embodiment as shown in Figure 1 it is 140°.

In operation, a pressurized carrier fluid is supplied to the nozzle unit 1 through inlet 2 from where it is jetted through the first nozzle 3 into the mixing chamber 5. Abrasive particles are supplied to the unit 1 through the abrasive particle inlet 4 into the mixing chamber 5, where they are mixed with the carrier fluid. The mix is then transported through the second nozzle 6, from where it leaves the nozzle unit 1 in the form of an abrasive jet. The abrasive jet can be directed against an object to be excavated.

The pressure differential over the fist nozzle 3 is typically between 100 and 700 bars. The high pressure jet diverges by approximately 8 to 9° as it leaves the first nozzle 3. With the relative dimensions of the nozzle

unit 1 as given above, the high pressure jet discharged from the first nozzle 3 into the mixing chamber 5, should completely enter into the second nozzle 6. In particular, by having the abrasive particle inlet 4 on one side of the mixing chamber 5 and the inside walls of the first and second nozzles on the opposing side in alignment with each other, it is achieved that the flow from the first nozzle 3 into the second nozzle 6 is optimized.

Figure 3 shows a schematic cross section of an excavation tool comprising a combination 10 of a nozzle unit 1, which may be the nozzle unit as shown in Figures 1 and 2, and a separation device 12 for magnetically separating abrasive particles from a fluid. For this tool the abrasive particles should comprise or be made of a magnetizable material, such as steel shot. The excavating tool 6 is provided with a longitudinal drilling fluid passage 11 in fluid communication with the nozzle unit 1 via inlet 2, for supplying the pressurized carrier fluid.

The separation device 12 comprises a magnetic body 13, rotatably arranged in a support sleeve 15. The magnetic body 13 generates a magnetic field for retaining the abrasive particles on the support sleeve 15. The inlet 4 for abrasive particles is located at the lower end of the support sleeve 15.

The magnetic body 13 has a central longitudinal shaft 18 and is rotatable relative to the sleeve 15 about the central longitudinal shaft 18. Drive means 19 are provided to drive shaft 18. The magnetic body 13 contains helical bands of increased magnetic field strength and helical bands of relatively low magnetic field strength.

The second nozzle 6 is arranged above an optional foot part 14, and is inclined relative to the

longitudinal direction of the excavation tool 10 at an inclination angle of 15-30° relative that direction, but other angles can be used. Preferably the inclination angle is about 21°, which is optimal for abrasively eroding the bottom of the bore hole 17 by axially rotating the complete excavation tool 10 about its longitudinal direction inside the bore hole 17.

In operation, the excavating tool 10 works as follows. The excavation tool 10 is connected to the lower end of the drill string (not shown) that is inserted into the borehole 17. The pressurized carrier fluid is supplied in the form of a drilling fluid that is pumped by a suitable pump (not shown), the drill string and the fluid passage 11 into the nozzle unit 1. During pumping, the drilling fluid is provided with a small amount of abrasive particles.

As explained above, the first nozzle 3 is arranged with a flow restriction, over which a pressure drop is present which drives the acceleration of the drilling fluid.

The drilling fluid flows through the mixing chamber 5 into the second nozzle 6, and is jetted against the borehole bottom 20. Simultaneously the excavation tool is rotated about its longitudinal axis. A return stream of drilling fluid and abrasive particles flows from the borehole bottom 20 through the annulus between the borehole 17 and the excavation tool, thereby passing along the support sleeve 15.

Simultaneously with pumping of the stream of drilling fluid, the magnet 13 is rotated about its shaft 18. Preferably the direction of rotation is opposite to that of the excavation tool on the drill string, the latter conventionally being clockwise when seen from the top of

the drill string. The magnet 13 induces a magnetic field extending to and beyond the outer surface of the support sleeve 15. As the return stream passes along the support sleeve 15, the abrasive particles in the stream are separated out from the stream by the magnetic forces from the magnet 13 which attract the abrasive particles onto the outer surface of the support sleeve 15.

The stream of drilling fluid, which is now substantially free from abrasive magnetic particles, flows further through the bore hole to the pump at surface and is re-circulated through the drill string after removal of the drill cuttings.

The magnetic abrasive particles retained on the support surface 15 are attracted towards the helical band having the highest magnetic field. Due to rotation of the magnet 13, and the helical bands of high and low magnetic field strengths, the abrasive particles are forced to follow a helically downward movement along the support sleeve 15.

As the particles arrive at the abrasive particle inlet 4, the stream of drilling fluid flowing from the first nozzle 3 into the mixing chamber 5 again entrains the abrasive particles. Thus, the abrasive particles are again jetted against the borehole bottom 20 and subsequently flow in upward direction through the borehole 17. The cycle is then repeated continuously.

In order to enhance the downward transport of the abrasive particles along the support sleeve 15, the support sleeve 15 may by slightly tapered to that its diameter at its lower end is smaller than at its upper end. A short tapered section 21 may be provided at the lower end of magnet 13 whereby the support sleeve 15 is provided with a corresponding conical taper in a manner

that the inlet 4 for abrasive particles provides fluid communication between the support surface 15 surrounding the tapered section 21 and the mixing chamber 5.

The conical taper is best based on the same angle as the above-discussed inclination angle of the second nozzle 6.

The support sleeve 15 as shown in Figure 3 is provided with a helically extending guide plates 24a and 24b protruding outwardly from the surface of the support sleeve 15. This guides the abrasive particles on their way down along the support sleeve 15. The downward transport velocity of the abrasive particles is increased if the guide plates run vertically parallel to the longitudinal axis. Preferably, the drilling fluid passage 11 can be provided in longitudinal contact with the support sleeve 15 as the guide plate, replacing the separate guide plates 24a and 24b.

Figure 4 shows a preferred magnetic body 13 in a cross sectional view (Fig. 4a), a longitudinal view (Fig. 4b), and a representation wherein the cylindrical surface of the magnetic body is unrolled flat in the plane of the paper (Fig. 4c). The cylindrical magnet 13 is preferably formed of eight smaller magnets 13a to 13h stacked together. A different number of smaller magnets can also be used. Each magnet 13a to 13h has diametrically opposed N and S poles, and the magnets are stacked in a manner that two essentially helical diametrically opposing bands are each formed by the N and S poles. Directly adjacent to the diametrically opposing bands, helical recesses are provided for achieving helical bands having lower magnetic permeability than the helical bands including the poles.

Due to the higher magnetic permeability of the magnet material than the less magnet material that fills up the recesses (a gas, a fluid, or a solid) the internal magnetic field lines predominantly follow the material of the magnet rather than the material contained in the recess. Thus, there exists a strong gradient zone between the bands containing the poles and the recesses. Instead of the recesses containing a gas, fluid or solid, there can be vacuum in the grooves. Figure 4a shows circular contours 24 around the diametrically opposing poles, connected by essentially straight contours 25. The straight contours correspond with the recess 26 and the circular contours with the parts of the magnet containing the poles.

In the vertical direction in Figure 4c, the height of the magnetic body is set out, which magnetic body is divided in smaller magnets 13a to 13h, and horizontally is set out the surface at all azimuths between 0 and 360°. As can be seen, the smaller magnets 13a to 13h are arranged such that their individual poles align in two helical bands, in the order of NSSNNSSN or SNNSSNNS. The angle θ of the helical recess 26 with the plane perpendicular to the shaft 18 is 53°.

Referring again to Figure 3, a magnetic attractor body 16 is preferably provided adjacent the mixing chamber on the side of the mixing chamber opposite to the abrasive particle inlet 4. This causes magnetic field lines to run from the lower end 21 of the magnet to this magnetic body. As a result, the magnetic field from the cylindrical magnet is pulled inside the mixing chamber 5. This achieves that the magnetic abrasive particles can form chains from the lower end of the support surface 15 towards the magnetic attractor body 16, thereby crossing

the jet that is discharged from the first nozzle 3. The particles in these chains thereby interact with the stream of drilling fluid passing through the mixing chamber 5, and thus the entrainment of these particles in the drilling fluid will be enhanced.

Suitable magnets can be made from any highly magnetisable material, including NdFeB, SmCo and AlNiCo-5, or a combination thereof. Preferably the magnet also has a magnetic energy content of at least 140 kJ/m^3 at room temperature, preferably more than 300 kJ/m^3 at room temperature such as is the case with NdFeB-based magnets.

The sleeve 15 and the drilling fluid passage 11 are best made of a non-magnetic material. Super alloys, including high-strength corrosion resistant non-magnetic Ni-Cr alloys, have been found to be particularly suitable. Other materials can be used including BeCu.

Typical dimensions relating to the excavating tool are given in the following table.

Part name	Reference number	size
Outer diameter of foot part	14	73 mm
Axial length of magnet	13	120 mm
Outer diameter of magnet	13	29 mm
Diameter in lower part of support surface	15	34 mm
Diameter in upper part of support surface	15	52 mm

The abrasive particles have a specific gravity (in the case of steel shot or steel grit particles: 7-8 SG), which is substantially higher than the typical specific

gravity of the drilling fluid (0,8-2.3 SG). This improves the situation that a relatively small volumetric entrainment rate of abrasive material is sufficient for a substantial kinetic energy transfer.

C L A I M S

1. Nozzle unit for generating an abrasive jet, which nozzle unit comprises:
- a first nozzle connected to a pressurized carrier fluid supply;
- a mixing chamber in which the first nozzle discharges;
- a second nozzle connected to the mixing chamber; and
- an abrasive particle inlet discharging in the mixing chamber;
wherein the proportion of the cross sectional area of the first nozzle opening and the cross sectional area of the second nozzle opening is in a range of 0.50-1.0.

2. Nozzle unit according to claim 1, wherein the length in flow direction of the mixing chamber is such, that taking into account the divergence of the jet to be discharged from the first nozzle, the diameter of the jet leaving the mixing chamber is smaller than the diameter of the second nozzle opening.

3. Nozzle unit according to claim 1 or 2, wherein the length in flow direction of the mixing chamber is in the range of 0.8-2.0 times the diameter of the first nozzle opening.

4. Nozzle unit according to any of the preceding claims, wherein the length in flow direction of the second nozzle is in the range of 4-10 times the second nozzle diameter.

5. Nozzle unit according to any of the preceding claims, wherein the second nozzle is eccentrically arranged relative to the first nozzle.

6. Nozzle unit according to claim 5, wherein the eccentric displacement of the second nozzle has a component in the direction of the abrasive particle inlet.

7. Nozzle unit according to claim 5 or 6, wherein at least part of an inside wall of the first nozzle is aligned with at least part of an inside wall of the second nozzle.

8. Nozzle unit according to any of the preceding claims, comprising a supply channel connected to the abrasive supply inlet, wherein the supply channel surrounds the mixing chamber by an angle of less than 180°.

9. Nozzle unit according to any of the preceding claims, comprising a supply channel connected to the abrasive supply inlet, wherein the included angle between the flow direction in the supply channel and an axis along the flow direction of the primary nozzle, is smaller than 60°.

10. Combination of a nozzle unit according to any of the preceding claims and a separation device for separating magnetical or magnetizable abrasive particles from a fluid, which separation device comprises a magnet body for attracting the abrasive particles out of a fluid flowing along the separation device, and a support surface at least partially enveloping the magnet body, and means for transporting attracted abrasive particles along the support surface to the abrasive particle inlet of the nozzle unit.

11. Method of excavating a hole into an object, comprising the steps of:
-    arranging an abrasive jet excavating tool comprising a nozzle unit according to any of the claims 1-9 into the hole;

- generating an abrasive jet by supplying a pressurized carrier fluid to the first nozzle and discharging abrasive particles into the mixing chamber; and
- directing the abrasive jet into the object.

A B S T R A C T

NOZZLE UNIT AND METHOD FOR EXCAVATING A HOLE IN AN OBJECT

Nozzle unit for generating an abrasive jet, which nozzle unit comprises:
- a first nozzle connected to a pressurized carrier fluid supply;
- a mixing chamber in which the first nozzle discharges;
- a second nozzle connected to the mixing chamber; and
- an abrasive particle inlet discharging in the mixing chamber;
wherein the proportion of the cross sectional area of the first nozzle opening and the cross sectional area of the second nozzle opening is in a range of 0.50-1.0.
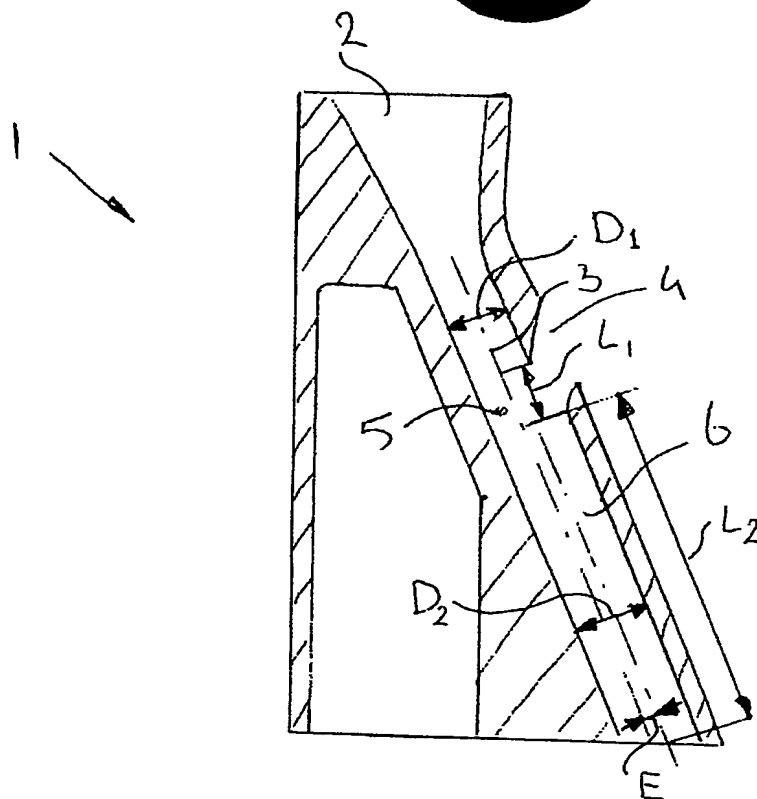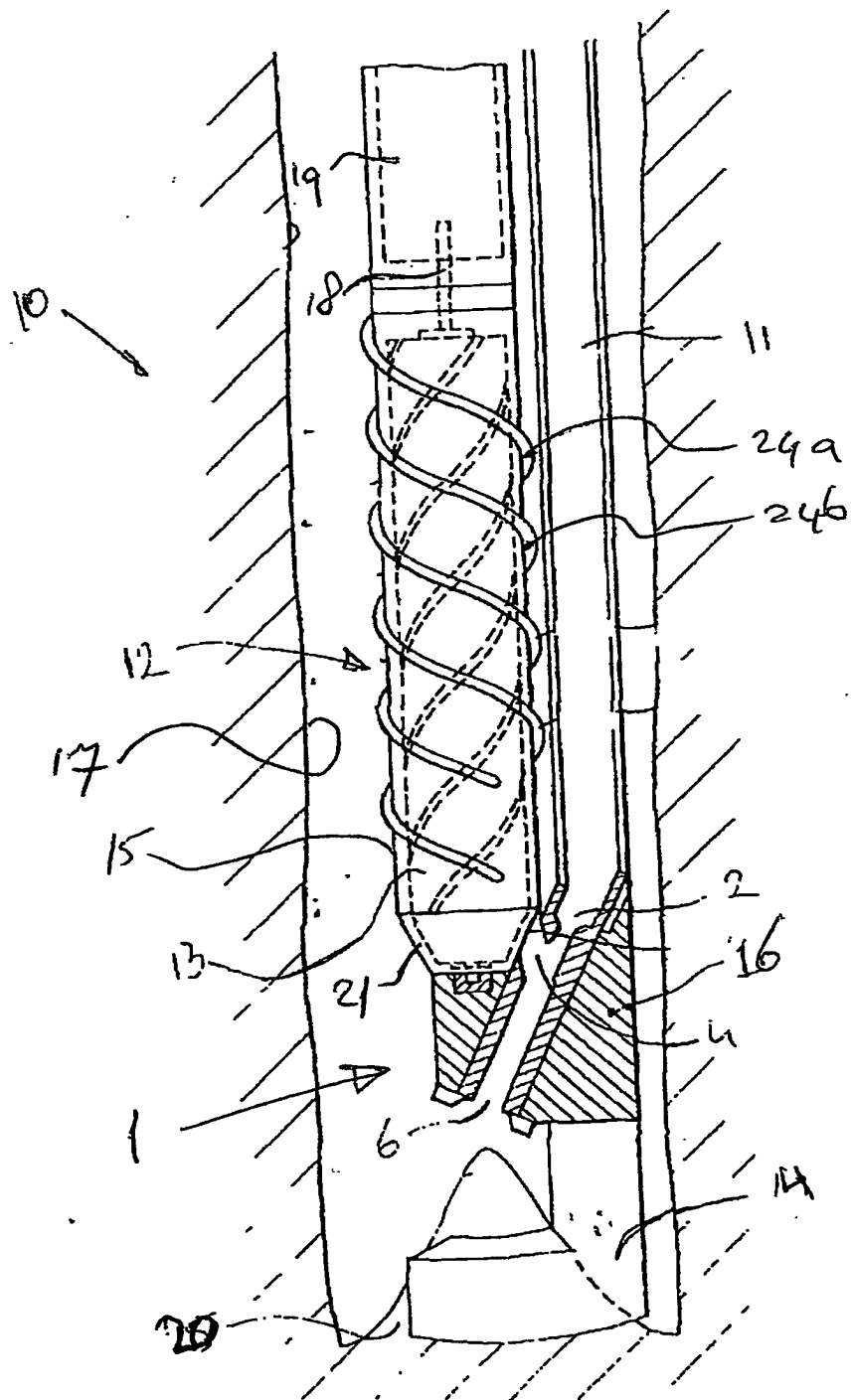
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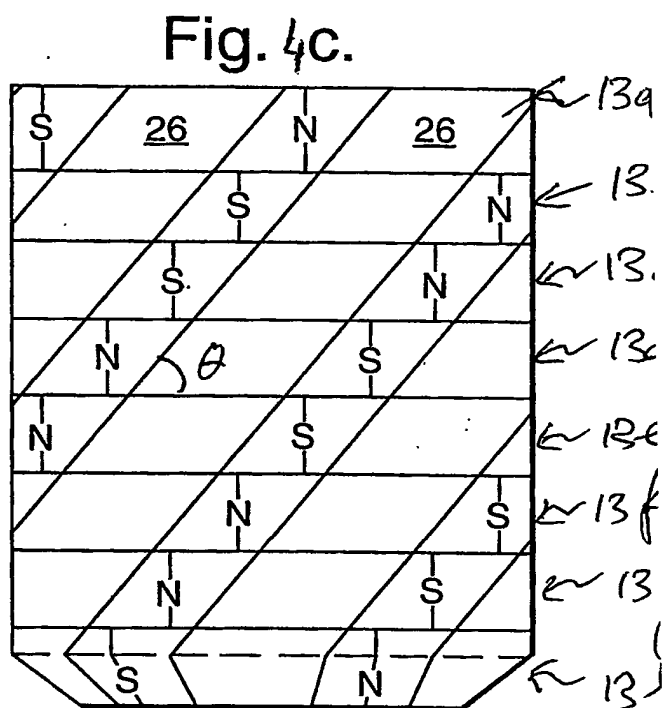
1

2

4

FIG 1

2

1

D_1

3 4

L_1

5

6

D_2

L_2

E

FIG 2

FIG 3

Fig. 4a.

24
25
N
24
25
S

Fig. 4c.

| S | 26 | N | 26 | 13a
| | | S | | N | 13
| | S. | | N | 13.
| | N | θ | S | 13c
| | N | | S | 13e
| | N | | S | 13f
| | N | | S | 13
| | S | | N | 13j

Fig. 4b.

13e
| S | 26 | 13f
| | N | 13g
| | S |
| S | 13h